SN 1987A: The Unusual Explosion of a Normal Type II Supernova

Nino Panagia

ESA/Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218, USA [panagia@stsci.edu]

Abstract. I review the unwrapping story the SN 1987A explosion event, and the main discoveries associated with it. I will show that, although this supernova is somewhat peculiar, the study of SN 1987A has clarified quite a number of important aspects of the nature and the properties of supernovae in general.

1. Introduction

Supernova 1987A was discovered on February 24, 1987 by Ian Shelton (Kunkel & Madore 1987) in the Large Magellanic Cloud. SN 1987A is the first supernova to reach naked eye visibility after the one studied by Kepler in 1604 AD and is undoubtedly the supernova event best studied ever by the astronomers. Actually, even if SN 1987A has been more than hundred times fainter than its illustrious predecessors in the last millennium, it has been observed in such a detail and with such an accuracy to make this event a *first* under many aspects (*e.g.* neutrino flux, progenitor identification, gamma ray flux) and definitely the *best* studied of all.

The early evolution of SN 1987A has been highly unusual and completely at variance with the *wisest* expectations. It brightened much faster than any other known supernova: in about one day it jumped from 12th up to 5th magnitude at optical wavelengths, corresponding to an increase of about a factor of thousand in luminosity. However, equally soon its rise leveled off and took a much slower pace indicating that this supernova would have never reached those high peaks in luminosity as the astronomers were expecting. Similarly, in the ultraviolet, the flux initially was very high, even higher than in the optical. But since the very first observation, made with the International Ultraviolet Explorer (IUE in short) satellite less than fourteen hours after the discovery(Kirshner *et al.* 1987, Wamsteker *et al.* 1987), the ultraviolet flux declined very quickly, by almost a factor of ten per day for several days. It looked as if it was going to be a quite disappointing event and, for sure, quite peculiar, thus not suited to provide any useful information about *"normal"* supernova explosions. But, fortunately, this proved not to be the case and soon it became apparent that SN 1987A has been the most valuable probe to test our ideas about the explosion of supernovae.

Reviews of both early and recent observations and their implications can be found in Arnett *et al.* (1989), McCray (1993, 2003, 2004), Gilmozzi and Panagia (1999), and Panagia (2003). In the following, I summarize some of the most interesting findings from SN 1987A studies.

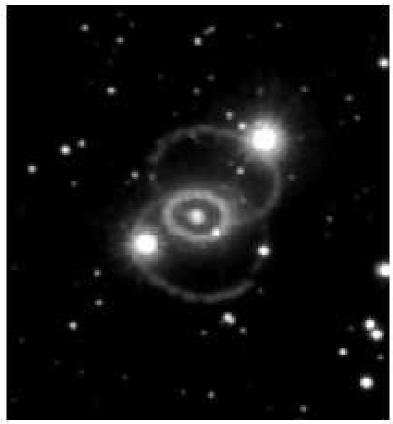

Figure 1. True color picture (*HST-WFPC2*) of SN 1987A, its companion stars, and the circumstellar rings (Courtesy of Peter Challis)).

2. Neutrino Emission from SN 1987A

For the first time ever, particle emission from a supernova was directly measured from Earth: on February 23, around 7:36 Greenwich time, the neutrino telescope "Kamiokande II" (a big cylindrical "tub" of water, 16 m in diameter and 17 m in height, containing about 3300 m^3 of water, located in the Kamioka mine in Japan, about 1000 m underground) recorded the arrival of 9 neutrinos within an interval of 2 seconds and 3 more 9 to 13 seconds after the first one. Simultaneously, the same event was revealed by the IMB detector (located in the Morton-Thiokol salt mine near Faiport, Ohio) and by the "Baksan" neutrino telescope (located in the North Caucasus Mountains, under Mount Andyrchi) which recorded 8 and 5 neutrinos, respectively, within few seconds from each other. This makes a total of 25 neutrinos from an explosion that allegedly produces 10 billions of billions of billions of billions of billions of billions of them! But a little more than two dozens neutrinos was enough to verify and confirm the theoretical predictions made for the core collapse of a massive star (*e.g.* Arnett *et al.* 1989 and references therein). This process was believed to be the cause of the explosion of massive stars at the end of their lives, and SN 1987A has provided the experimental proof that the theoretical model was sound and correct, promoting it from a nice theory to the description of the truth.

3. SN 1987A Progenitor Star

From both the presence of hydrogen in the ejected matter and the conspicuous flux of neutrinos, it was clear that the star which had exploded was quite massive, about twenty times more than our Sun. And all of the disappointing peculiarities were due to the fact that just before the explosion the supernova progenitor was a blue supergiant star instead of being a red supergiant as common wisdom was predicting. There is no doubt about this explanation because

SN 1987A is exactly at the same position as that of a well known blue supergiant, Sk -69° 202. And the IUE observations indicated that such a star was not shining any more after the explosion: the blue supergiant star unambiguously was the SN progenitor. This heretic possibility was first suggested in Panagia *et al.* (1987) and subsequently confirmed by the more detailed analyses presented by Gilmozzi *et al.* (1987) and Sonneborn, Altner & Kirshner (1987).

On the other hand, the presence of narrow emission lines of highly ionized species, detected in SN 1987A short wavelength spectrum since late May 1987, has provided evidence for the progenitor having been a red supergiant before coming back toward the blue side of the HR diagram (Fransson *et al.* 1989). Also, the detection of early radio emission that decayed in a few weeks (Turtle *et al.* 1987) indicated that the ejecta were expanding within a circumstellar environment whose properties were a perfect match to the expected wind of a blue supergiant progenitor (Chevalier & Dwarkadas 1995).

Such an evolution for an $\sim 20\ M_\odot$ star was not expected, and theorists struggled quite a bit to find a plausible explanation for it. As summarized by Podsiadloswki (1992), in order to explain all characteristics of SN 1987A, rotation has to play a crucial role, thus limiting the possibilities to models involving either a rapidly rotating single star (Langer 1991), or a stellar merger in a massive binary system (Podsiadloswki 1992).

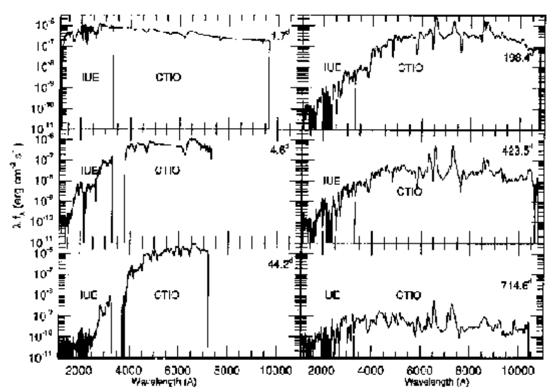

Figure 2. Evolution of the UV and optical spectrum of SN 1987A (Pun et al. 1995).

4. Explosive Nucleosynthesis

The optical flux reached a maximum around mid-May, 1987, and declined at a quick pace until the end of June, 1987, when rather abruptly it slowed down, settling on a much more gentle decline of about 1% a day (Pun *et al.* 1995). Such a behaviour was followed for about two years quite regularly: a perfect constant decay with a characteristic time of 114 days, just the same as that of the radioactive isotope of cobalt, ^{56}Co, while transforming into iron. This is the best evidence for the occurrence of nucleosynthesis during the very explosion: ^{56}Co is in fact the product of ^{56}Ni decay and this latter can be formed at the high temperatures which occur after the core collapse of a massive star. Thus, not only are we sure that such a process is operating in a supernova explosion, but we can also determine the mass of Ni produced in the explosion, slightly less than 8/100 of a solar mass or $\sim$1% of the mass of the stellar core before the explosion. The detection of hard X-ray emission since July 1987, and the subsequent detection of gamma-ray emission have confirmed the reality of such a process and provided more detailed information on its distribution within the ejecta (*e.g.* Arnett *et al.* 1989 and references therein). Eventually, the detection of Ni lines in the near infrared (Spyromilio *et al.* 1990) confirmed the light curve result and provided the first *direct* evidence of the production of ^{56}Ni in supernova explosions.

5. Energetics of the Emitted Radiation

A catalog of SN 1987A ultraviolet spectra obtained with *IUE* (751 spectra over the period 1987 February 24 [day 1.6] through 1992 June 9 [day 1567]) have been presented by Pun *et al.* (1995). They show that the UV flux plummeted during the earliest days of observations (Fig. 2) because of the drop in the photospheric temperature and the increase in opacity. However, after reaching a minimum of 0.04% on day 44, the UV flux increased by 175 times in its contribution to 7% of the total UVOIR bolometric luminosity at day 800 (Fig. 3). A study of the UV colors reveals that the supernova started to get bluer in the UV around the time when dust started to form in the ejecta. These results are consistent with the possibility that the dust condensed may be metal-rich.

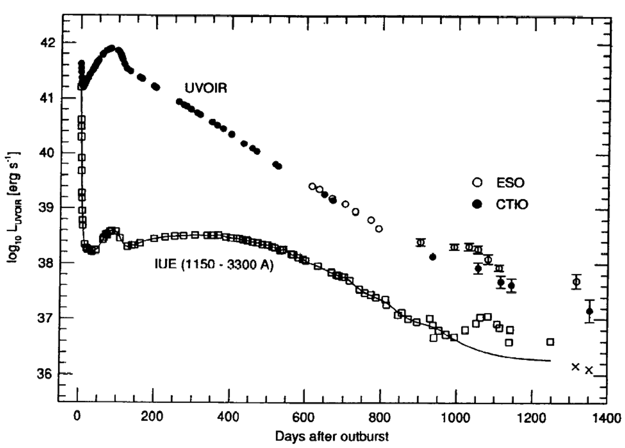

Figure 3. UV and bolometric light curve of SN 1987A (Pun et al. 1995).

6. The UV Echo of SN 1987A: Spectrum of the Explosion

Bright transient events such as nova and supernova outbursts can give rise to the phenomenon of a light echo. This is produced when light from the explosion illuminates nearby interstellar dust and is reflected in the direction of the observer. In the case of SN 1987A echoes were predicted by Chevalier (1986) and

Schaefer (1987), and first detected by Crotts (1988) and Rosa (1988). Since the UV light curve was already plummeting by the time of the first IUE observation, a UV echo is expected to be the reflection of the light emitted at the very time of the explosion (i.e. *before* the discovery of the supernova!). Indeed, ultraviolet light emitted by SN 1987A at the shock breakout was detected by means of IUE observations, made one year apart from each other, at a location a few arcseconds outside a bright portion of an optical echo (Gilmozzi & Panagia 1999). The spectrum of the echo shows a hot continuum and a wide P Cyg-like feature centered around 1500Å (Fig. 4) which, if interpreted as CIV 1550Å, implies an expansion velocity at the time of the shock breakout as high as 40,000 km s^{-1}. This is in agreement with the first "direct" IUE spectrum, taken 24 hours after the explosion, which showed a MgII line with a terminal velocity of about 35,000 km s^{-1}(Kirshner *et al.* 1987).

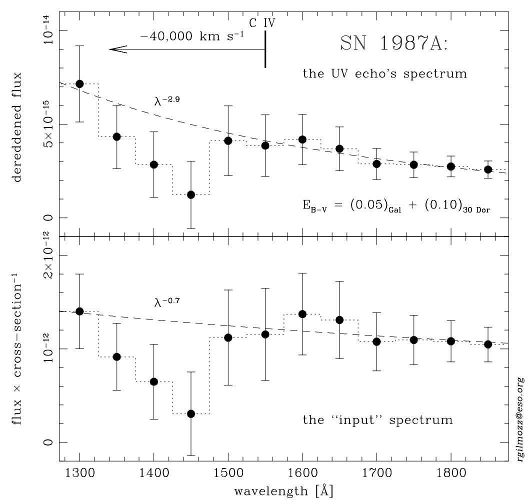

Figure 4. The spectrum of the UV echo. **Upper panel:** dereddened observed data. **Lower panel:** the effect of dust scattering has been "removed" to reveal the actual shape of the spectrum at the shock breakout.

7. HST Observations - Structure and Expansion of the Ejecta

The Hubble Space Telescope (*HST*) was not in operation when the supernova exploded, but it did not miss its opportunity in due time and its first images, taken with the *ESA-FOC* on August 23 and 24, 1990, revealed the inner circumstellar ring in all its "glory" and detail (*cf.* Jakobsen *et al.* 1991), showing that, even with spherical aberration, *HST* was not a complete disaster, after all. More observations were made with the *FOC*, which allowed Jakobsen *et al.* (1993, 1994) to measure the angular expansion of the supernova ejecta. The results confirmed the validity of the expansion models put forward on the basis of spectroscopy. Additional observations, made with the *WFPC2* on the re-refurbished *HST* confirmed the early trend of the expansion and revealed the presence of structures that had never been seen before (Jansen & Jakobsen 2001, Wang *et al.* 2002).

HST-FOS spectroscopic observations of SN 1987A, made over the wavelength range 2000-8000 Å on dates 1862 and 2210 days after the supernova outburst, indicate that at late times the spectrum is formed in a cold gas that is excited and ionized by energetic electrons from the radioactive debris of the supernova explosion (Wang *et al.* 1996). The profiles are all asymmetric, showing redshifted extended tails with velocities up to 10,000 km s^{-1} in some strong lines. The blueshift of the line peaks is attributed to dust that condensed from the SN 1987A ejecta and is still distributed in dense opaque clumps.

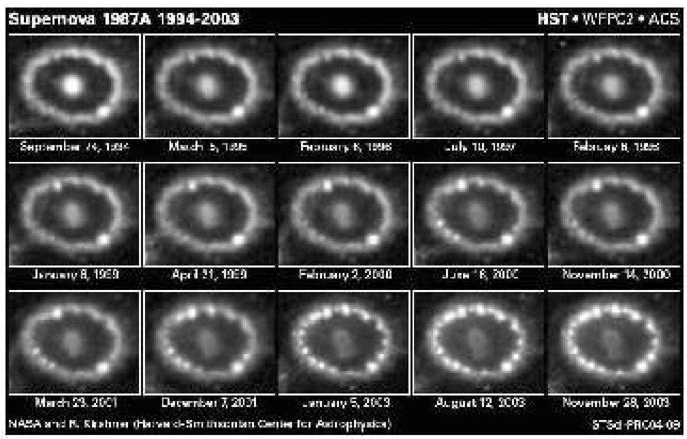

Figure 5. Series of images of SN 1987A and its inner circumstellar ring obtained with *HST-WFPC2* between September 1994 and November 2003. It appears that the quiescent ring has developed at least twenty hot spots in the last seven years. [Courtesy of R.P Kirshner (Harvard) and NASA]

8. Properties and Nature of the Circumstellar Rings

The study of the circumstellar rings, *i.e.* an equatorial ring (the "inner ring") about 0.86" in radius and inclined by about 45 degrees, plus two additional "outer rings" which are approximately but not exactly, symmetrically placed relative to the equatorial plane, approximately co-axial with the inner ring, and have sizes 2-2.5 larger than the inner ring. The presence of the inner ring was originally revealed with the *IUE* detection of narrow emission lines (Fransson *et al.* 1989). Heroic efforts done with ground based telescopes (Crotts *et al.* 1989, Wampler *et al.* 1990) provided early measurements of the shapes of the circumstellar rings. Subsequently the rings were superbly imaged by *HST* using both the *FOC* and *WFPC2* cameras (*e.g.* Jakobsen *et al.* 1991, Burrows *et al.* 1995). Detailed studies of the rings, mostly based on spectroscopy and imaging done with *HST*, have suggested that the rings, characterized by strong N overabundances (Fransson *et al.* 1989, Panagia *et al.* 1991, Panagia *et al.* 1996, Lundqvist & Fransson 1996, Sonneborn *et al.* 1997), were ejected in two main episodes of paroxysmal mass loss which occurred approximately 10,000 (the inner ring) and 20,000 years (the outer rings) before the supernova explosion, respectively (Panagia *et al.* 1996, Maran *et al.* 2000).

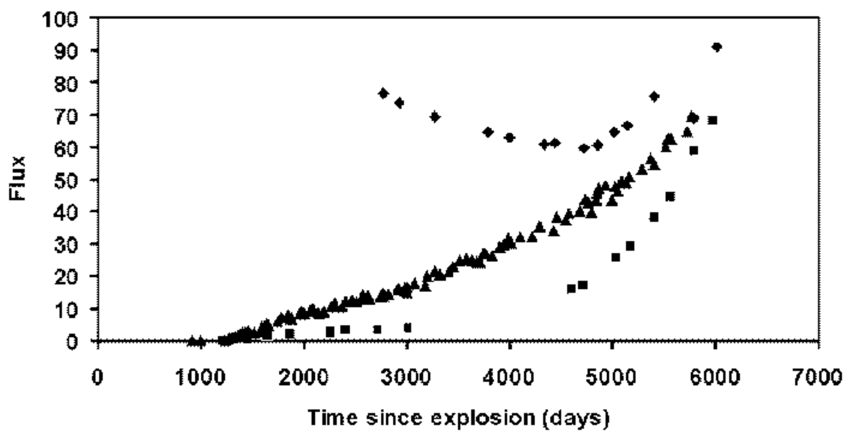

Figure 6. The late evolution of the ring emission in the optical (diamonds), radio (triangles) and X-ray (squares) domains [adapted from McCray 2004]

9. Interaction of the Ejecta with the Equatorial Ring

Since mid-1997 Hubble has observed the high-velocity material from the supernova explosion starting to overtake and crash into the slow-moving inner ring. Figure 5 shows the dramatic evidence of these collisions. The circumstellar ring started to develop bright spots in 1997, and in November 2003 one can identify at least twenty bright spots. These bright spots are the result of the fast moving component of the ejecta (at a speed of about 15,000 km s^{-1}) colliding with the stationary equatorial ring (*e.g.* Sonneborn *et al.* 1998, Michael *et al.* 2003). Independent evidence for an interaction whose strength is quickly increasing with time is provided by both radio (Manchester *et al.* 2002) and X-ray (Park *et al.* 2002) emission (*cf.* Figure 6). Over the next decades, as the bulk of the ejecta reach the ring, more spots will light up and the whole ring will shine as it did in the first several months after explosion (*e.g.* McCray 2004). Eventually, the ejecta will completely sweep the ring up, clearing the circumstellar space of that beautiful remnant of the pre-supernova wind activity.

10. SN 1987A: An Ongoing Experiment

It is clear that SN 1987A constitutes an ideal laboratory for the study of supernovae, and of explosive events, in general. As summarized above, a great deal of observations have been made and quite a number of aspects have been clarified and understood. At the same time, there are still important points that need clarification and further study, as well as more observations. For example, the stellar remnant left behind by the explosion has eluded our detection so far and its nature remains a complete mystery. Also, the detection of an early interaction of the supernova ejecta with the inner circumstellar ring has opened a new chapter in the study of this supernova, that is expected to culminate in about ten years, when the colliding materials will become the brightest objects in the LMC, with a display of fireworks at X-ray, UV and optical wavelengths that defy our most vivid imagination.

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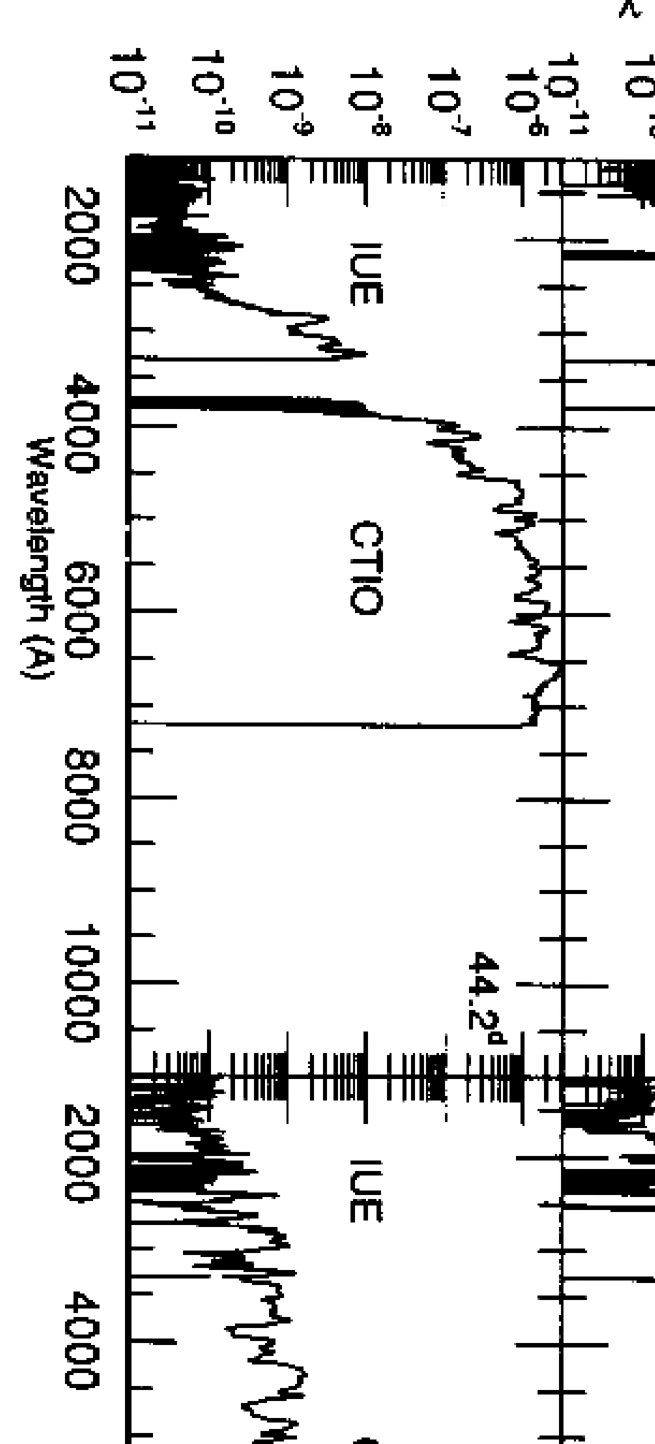

IUE
CTIO
44.2d
Wavelength (A)
2000
4000
6000
8000
10000